

## Proton Driver II Design Study



- FNAL Directorate has initiated PD2 Design Study
- Goal is 5x more protons in Main Injector.
- Side-by-side studies (*including cost*) of:
  - Optimized 8 GeV Booster Synchrotron
  - 8 GeV Superconducting Linac
  - Main Injector modifications for increased beam current

*This is mainly a technical talk on the 8 GeV Linac.*

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## 8 GeV Injector Linac Concept



- 1) Copy SNS Linac design up to 1.2 GeV  
*(Reduced beam current and relaxed schedule allow some design optimizations)*
- 2) Use “TESLA” Cryomodules from 1.2 → 8 GeV
- 3) H<sup>-</sup> Injection at 8 GeV in Main Injector

⇒ **“Super-Beams” in Fermilab Main Injector:**

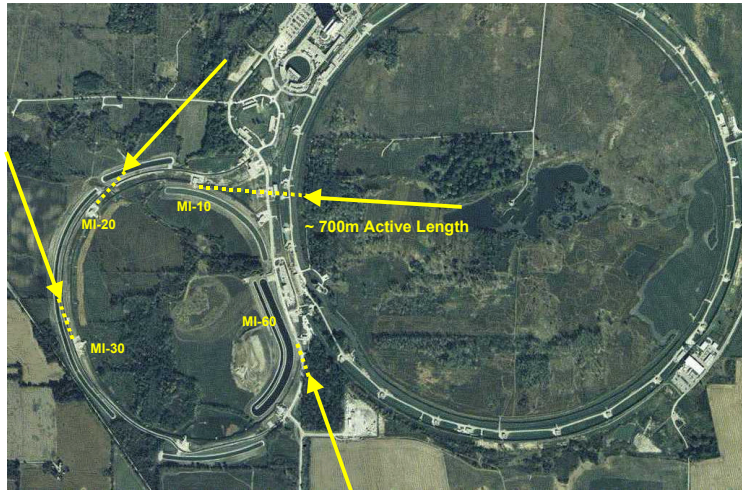
*2 MW Beam power, small emittances, and minimum (1.5 sec) cycle time*

- Other possible missions for unused linac cycles:
  - 8 GeV  $\nu$  program, 8 GeV electrons ==> XFEL, etc.

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## 8 GeV Injector Linac - Possible Sitings



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## 8 GeV Linac Parameters

### 8 GeV LINAC

Energy	GeV	8	
Particle Type	H- Ions, Protons, or Electrons		
Rep. Rate	Hz	10	
Active Length	m	671	
Beam Current	mA	25	
Pulse Length	msec	1	
Beam Intensity	P / pulse	1.5E+14	(can be H-, P, or e-)
	P/hour	5.4E+18	
Linac Beam Power	MW avg.	2	
	MW peak	200	

### MAIN INJECTOR WITH 8 GeV LINAC

MI Beam Energy	GeV	120	
MI Beam Power	MW	2.0	
MI Cycle Time	sec	1.5	filling time = 1msec
MI Protons/cycle		1.5E+14	5x design
MI Protons/hr	P / hr	3.6E+17	
H-minus Injection	turns	90	SNS = 1060 turns
MI Beam Current	mA	2250	

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## Benefits of 8 GeV Injector



- Benefits to V and Fixed-Target program
  - solves proton economics problem:  $> 5E18$  Protons/hr at 8 GeV
  - operate MI with small emittances, high currents, and low losses
- Benefits to Linear Collider R&D
  - 1.5% scale demonstration of TESLA economics
  - Evades the Linear Collider R & D funding cap
  - Simplifies the Linear Collider technology choice
  - Establishes stronger US position in LC technology
- Benefits to Muon Collider / n-Factory R&D
  - Establishes cost basis for P-driver and muon acceleration
- Benefits to VLHC: small emittances, high Luminosity
  - $\sim 4x$  lower beam current reduces stored energy in beam
  - Stage 1: reduces instabilities, allows small beam pipes
  - Stage 2: injection at final synchrotron-damped emittances

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## Main Injector with 8 GeV Linac

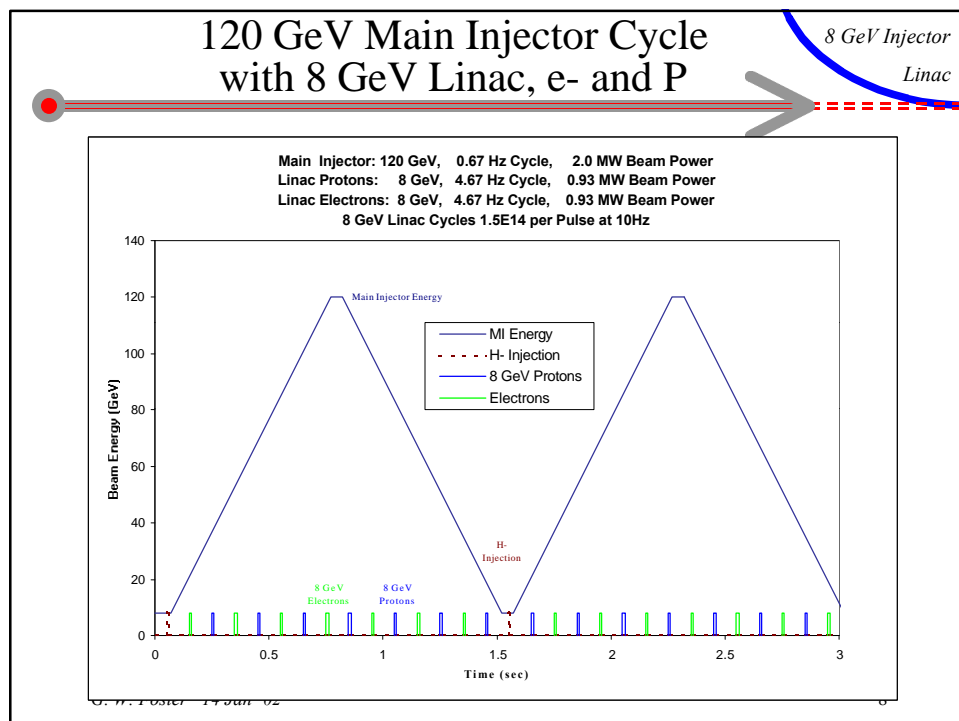
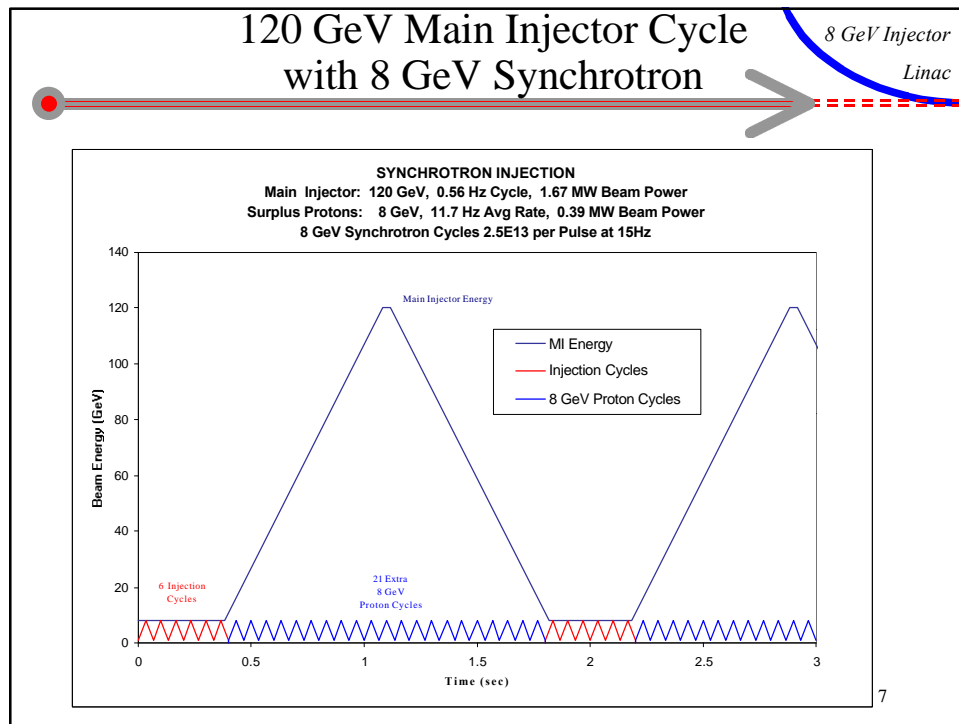


- 1.5 Second Cycle time to 120 GeV
  - filling time 1 msec or less
  - no delay for multiple Booster Batches
  - no beam gaps for “Booster Batches” -- only Abort gap
- H<sup>-</sup> stripping injection at 8 GeV
  - 25 mA linac beam current
  - 90-turn Injection gives MI Beam Current  $\sim 2.3$  A  
(SNS has 1060 turn injection at 1 GeV)
  - preserve linac emittances  $\sim 0.5\pi$  (95%) at low currents
  - phase space painting needed at high currents

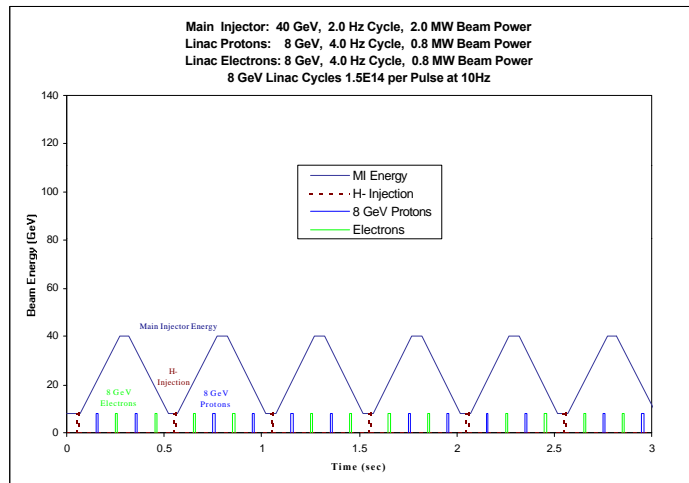
*® can put a frightening amount of beam in MI*

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## 8 GeV Linac Allows Reduced MI Beam Energy without Compromising Beam Power

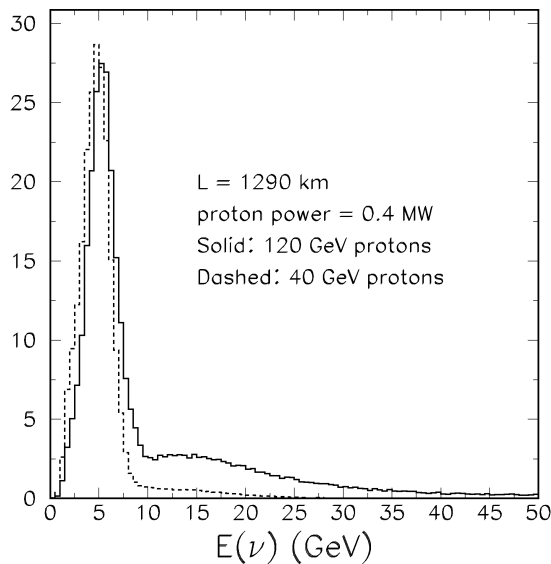


MI cycles to 40 GeV at 2Hz, retains 2 MW MI beam power

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## Running at Reduced Proton Energy Produces a Cleaner Neutrino Spectrum



Running at 40 GeV reduces tail at higher neutrino energies.

Same number of events for same beam power.

(Plot courtesy Fritz & Debbie)

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## Very Rough Cost Estimates

8 GeV Injector  
Linac

- 1) Scaled from TESLA costs
- 2) Scaled from SNS actual costs
- 3) First stab at bottom-up cost est.
  - use SNS actual costs where reasonable
  - independent, bottom-up cost estimates elsewhere
  - *Not yet completed but this is the way to go.*

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## Rough Cost, Scaled from TESLA

8 GeV Injector  
Linac

- TESLA Project Cost (European) \$3B
- subtract damping rings, IR, Injector \$2.5B
- US Cost Basis (x2) for bare linac \$5B
- Scale to 7 GeV  $(7/500) = 1.4\%$  \$70M
- TESLA Quantity Discount  $(7/500)^{-0.074} = 1.37$  \$100M
- Include Fixed Project Cost (\$50M??) **\$150M**

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## Rough Cost, Scaled from SNS

- SNS Project Cost \$1300M
- SC Linac Cost (approx, incl. civil) \$250M
- Scale SCRF by energy ( $7.6/0.8$ ) x10

**\$2.5 B**

*There are many good technical reasons why the TESLA linac should be cheaper. But how much?*

*We need detailed breakdowns to understand the apparent disconnect between TESLA and SNS cost estimates.*

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## Bottom-up Cost for 8 GeV - the game plan:

- Can use SNS Actual Costs for:
  - Niobium
  - Finished Cavities (industrially produced)
  - Klystrons, circulators, and RF couplers
  - Civil construction for Linac & associated buildings
  - Cryogenics and Cryoplant including civil
- T. Nicol independent cost est. for TESLA style Cryostat, and Assembly
- FNAL Bottom-up Cost Est. for TESLA-Style RF
- MI actual costs for tunnel, Beam Dump, etc.
- FMI for Controls & Project Overhead

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## Design Optimizations of SNS Linac

- The Spallation Neutron Source (SNS) is a well organized and documented project, and a good model for many aspects of the 8 GeV Linac.
- Design optimizations possible for 8 GeV Injector:
  - Lower average beam current and pulse rate (10 Hz vs. 60Hz)
  - Higher accelerating gradients can be assumed due to successful SC Cavity R&D by SNS, TJNAF, TESLA, Cornell, KEK, et.al.
  - Less schedule pressure allows for additional component development where cost-effective
- 8 GeV Linac can marry the best of TESLA, CEBAF, and SNS system designs

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## Which Optimizations of SNS are worth it?

### 1) TESLA-style RF fanout

- drive many (8-12) cavities from single big klystron
- must complete SNS development of fast phase shifter

### 2) Eliminate warm Cavity-Coupled Linac (CCL)

- Use Beta=0.47, 805 MHz Superconducting cavities developed for RIA project by NSCL/Jlab/INFN
- Similar cryomodules & RF as Beta=0.61, 0.81 cavities
- SNS considered this but dropped due to schedule

### 3) Use TESLA-style cryomodules with cold quads

- longer cryomodules with fewer end costs

### 4) Civil construction for fewer klystrons per meter

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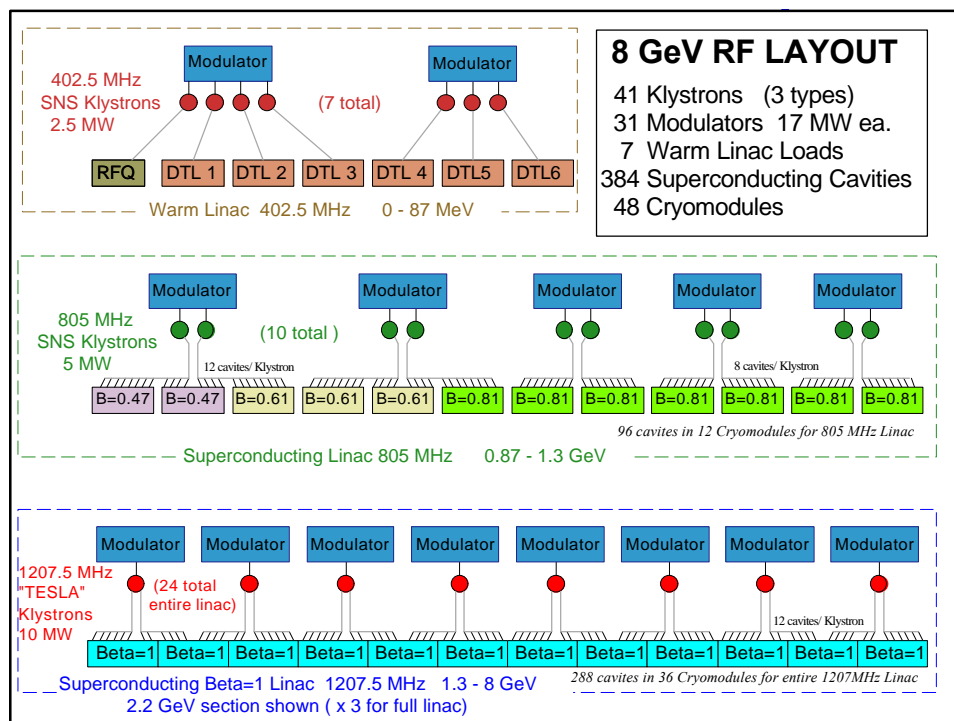
# Layout of 8 GeV Linac

8 GeV Injector  
Linac

- Copy SNS Front-end, RFQ, DTL up to 87 MeV
- 805 MHz Superconducting Linac up to 1.2 GeV
  - Three sections: Beta = 0.47, 0.61, 0.81
  - Use cavity designs developed for SNS & RIA
  - TESLA-style cryomodules for higher packing factor
- 1.2 GHz “TESLA” cryomodules from 1.2-8 GeV
  - This section can accelerate electrons as well
  - RF from one Klystron fanned out to 12 cavities

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# Linac: 0 - 87 MeV

8 GeV Injector  
Linac

Copy of SNS Front End and Drift-Tube Linac (DTL) 0 @ 87 MeV

Eight 402.5 MHz, 2.5 MW Klystrons      Total Length ~45m

- Direct Copy of SNS Design:
  - Ion Source
  - RF Quadrupole (RFQ)
  - Low-Energy Beam Transport (buncher & chopper)
  - Drift Tube Linac (402.5 MHz Normal Conducting)

*SNS work provides technical existence proof*

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## At Reduced RF Duty Cycle of ~1%, the Front End is a Commercial Product

8 GeV Injector  
Linac

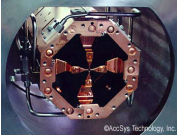
**AccSys**  
TECHNOLOGY, INC.

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**CUSTOM LINAC SYSTEMS**

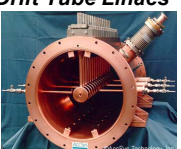
AccSys' proprietary and patented linac technology can provide a wide range of ion beams and energies for specialized applications in research and industry. AccSys experts will design a system to customer specifications consisting of a carefully selected combination of our standard modular subsystems: radiofrequency quadrupole (RFQ) linacs, drift tube linacs (DTL), rf power systems and/or other components such as high energy beam transport (HEBT) systems and buncher cavities.

**Radio Frequency Quadrupole Linacs**



AccSys' patented Univane (US Patent No. 5,315,120) design provides a robust, cost-effective solution for low-velocity ion beams. This unique geometry incorporates four captured rf seals, is easy to machine, assemble and tune, and is inexpensive to fabricate. The extruded structure, which is available in lengths up to three meters, can accelerate ions injected at 20 to 50 keV up to 4 MeV per nucleon. Cooling passages in the structure permit operation at duty factors up to 25%.

**Drift Tube Linacs**



Drift Tube Linacs provide a cost-effective solution for ion beam energies above a few MeV per nucleon. Designed to accelerate ions from an RFQ, the DTL's permanent magnet focusing and high rf efficiency result in a minimum cost per MV. AccSys' patented drift tube mounting scheme (US Patent No. 5,179,350), which is integral to the twin-beam welded vacuum tank, provides excellent mechanical stability and low beam loss.

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*D. Young's work...*

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## Commercially Available Front-End Linac (AccSys)

- Don Young has verified the applicability of the AccSys RFQ/DTL to various PD scenarios.
- This is a real product. Accsys has shipped multiple RFQ/DTL units for medical purposes in recent years.
- Estimate ~\$20M for turn-key operation @87MeV  
(Less if FNAL provides the RF/Klystron/modulator)
- This is very interesting for FNAL to pursue no matter what becomes of PD2 study.

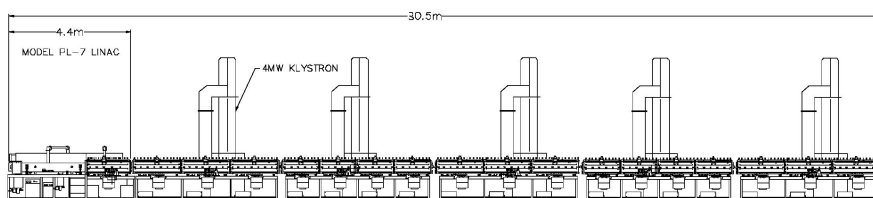
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## AccSys Source/RFQ/DTL



- AccSys PL-7 RFQ with one DTL tank



- Appears to have shorter length and lower price than cloning the SNS Linac, *for 10 Hz operation*

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*D. Young's work...*

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## SC Linac: 87 -186 MeV

*8 GeV Injector Linac*

**Beta=0.47 Superconducting Linac    87 ® 186 MeV**

( 2 Cryomodules, 2 Klystrons, Length ~24m)

- Replace Cavity-Coupled (Warm) Linac of SNS design with 805 MHz Superconducting Linac
- Cold quads and long cryomodules reduce length to ~25m
- Use Beta=0.47 Cavities developed for RIA by INFN/Jlab/MSU collaboration
- RF fanout with fast phase shifters on each cavity

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## SC Linac: 186 - 400 MeV

*8 GeV Injector Linac*

**Beta=0.61 Superconducting Linac    186 ® 400 MeV**

( 3 Cryomodules, 3 Klystrons, Length ~36m)

- Same Cavities, Couplers, etc. as SNS “medium-Beta”
- Higher assumed gradients reduce # cavities from 33 to 24
- Cold quads and long cryomodules reduce length to ~35m

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## SC Linac: 400-1150 MeV

8 GeV Injector Linac

**Beta=0.81 Superconducting Linac 400 @ 1000 MeV**

( 7 Cryomodules, 7 Klystrons, Length ~91m)

- Same Cavities as SNS “High-Beta”
- Same assumed gradient and # cavities as SNS  
( higher assumed gradient could raise output energy above 1 GeV )
- Cold quads and long cryomodules reduce length to ~60m

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## “TESLA” style Linac: 1.2 → 8 GeV

8 GeV Injector Linac

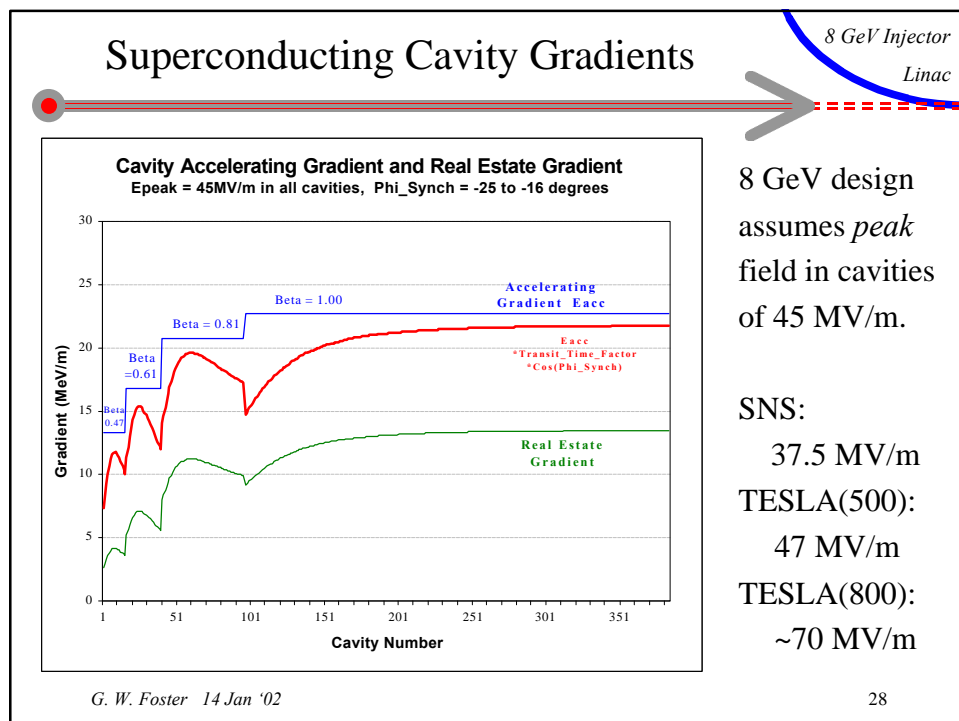
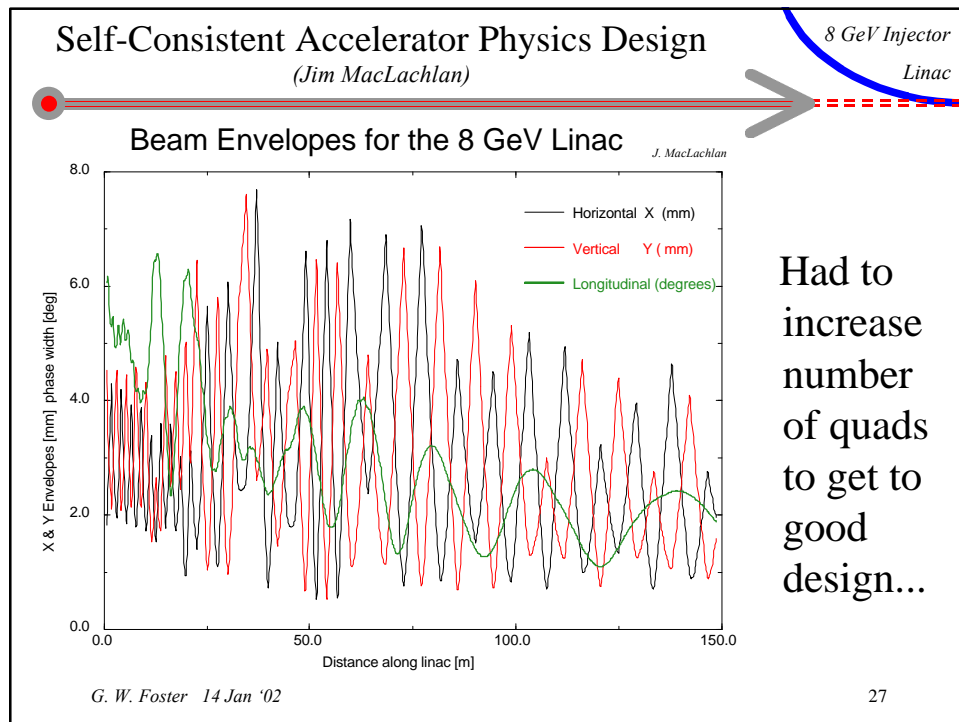
**Beta=1 Superconducting 1207.5 MHz LINAC 1 @ 8 GeV**

( 30 Cryomodules, 30 Klystrons, Length ~480m)

- 30 TESLA-style Cryomodules
- 30 Klystrons with 10:1 TESLA-style RF fanout  
( requires fast phase shifters/attenuators on each leg )
- 480 m length for 1.3 → 8 GeV

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## SNS Cavity Fabrication

8 GeV Injector  
Linac


Deep drawing & machining



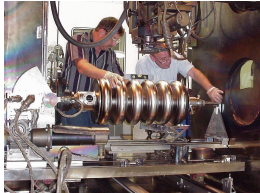
Dumb-bells




Frequency adjust



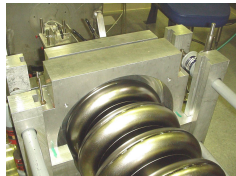
Welding



SNS  $\beta=0.61$



Tuning




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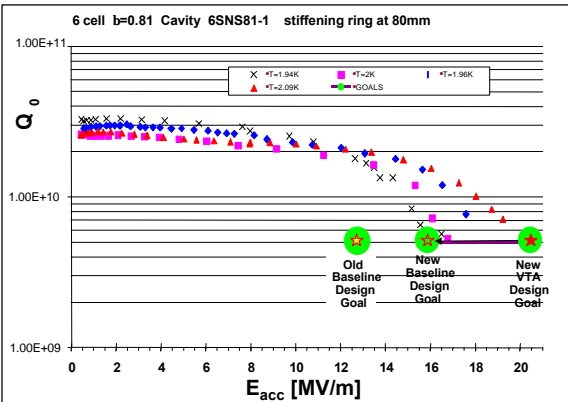
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## SNS $\beta = 0.81$ Tests at TJNAF

8 GeV Injector  
Linac



6 cell  $b=0.81$  Cavity 6SNS81-1 stiffening ring at 80mm



[from N. Holtkamp Nov '01 SNS Review]

**$E_{acc} > 20$  MV/m for protons  
is now reasonable design goal**

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## SNS Cavity Costs

8 GeV Injector  
Linac

- SNS recently ordered 109 cavities 1.2m long for:  
(\$4M Niobium + \$4.5M fab & process)  
~ \$80k per cavity
- The 8 GeV Linac needs 380 cavities 1.2m long  
(~ 400 including spares)  $\Rightarrow$  **\$32M for 8 GeV**
- This assumes:
  - no quantity discount or rebate for existing tooling
  - that 1.2 GHz 9-cell cavities are the same price as  
805 MHz 6-cell SNS cavities of same length

***P The cavity cost should not blow the budget***

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## CRYOMODULES

8 GeV Injector  
Linac

### BIG Differences between SNS & TESLA

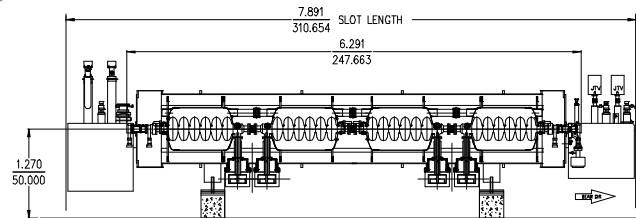
- Key Specification:
  - **SNS** Cryomodules can be swapped out in ~1 shift
  - **TESLA** cryomodule failure take 25 days to fix
    - comes from having 2.5km section of linac
  - **8 GeV LINAC**: ~2 day repair time specified
    - possible because linac sector is much shorter ~300m

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## SNS/CEBAF Cryomodules

8 GeV Injector  
Linac



- Warm-to-cold beam pipe transition in each module
- 2K Coldbox, J-T & HTX in each Cryomodule
- Bayonet disconnects at each coldbox
- Only 2-4 cavities per cryomodule

*Expensive Design forced by fast-swap requirement*

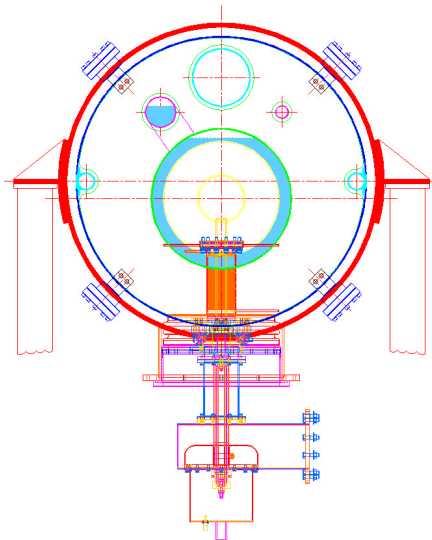
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## TESLA-Style Cryomodules for 8 GeV

(T. Nicol)

8 GeV Injector  
Linac

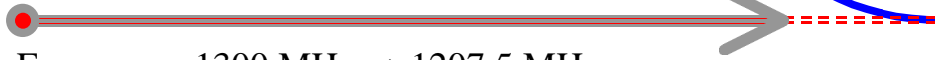


- Design conceptually similar to TESLA
- No warm-cold beam pipe transitions
- No need for large cold gas return pipe
- Cryostat diameter can be *smaller* than TESLA (same as LHC)

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## Scaling of TESLA Cryomodules for 1-8 GeV



**Frequency:** 1300 MHz  $\rightarrow$  1207.5 MHz

- for compatibility with 805 MHz front-end Linac
- 1.2 GHz cavities must be  $\sim 8\%$  larger than TESLA
- 8 Cavities per Cryomodule not 12 (TESLA)

### Accelerating Gradient for Protons

- Assume Eacc  $\sim 23$  MeV/m (Epeak $\sim 45$  MV/m)
- Protons Linacs must run off-crest for phase stability ( $\cos \sim 0.9$ )

### Number of Quadrupoles

- 8 GeV requires 2 quads per 16m cryomodule not 1/3
- Quads must be long  $\sim 1$ m to avoid H- stripping from B-field

**Vacuum Breaks:** every  $\sim 80$ m not 500m (design choice)

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## Scaling of TESLA Cryomodules for 1.3-8 GeV



		TESLA	8 GeV
Frequency	MHz	1300	1207.5 frequency constraint from existing linac
Peak Field in Cavity Epeak	MV/m	47	45
Accelerating Gradient Eacc	MV/m	23.5	22.5 Epeak/Eacc=2.0 for TESLA design
cos(Synchronous Phase)		1	0.9 proton cavities run off-crest, lose gradient
Accelerating Gradient * Cos(Phi)	MV/m	25	20.25
Cavities per Cryomodule		12	10
Quadrupoles per cryomodule		0.333	1
Number of cells / cavity		9	9
Cavity Active Length	m	1.04	1.12 TESLA TDR fig 2.1.3; scale by freq.
Length incl. Couplers&Bellows	m	1.32	1.42 TESLA TDR fig 3.3.1; scale by freq
Quad Assy Length	m	0.864	1.2 TDR fig 3.3.3; 8 GeV quads weak(stripping)
Cryomodule Interconnect L	m	0.38	0.50 TDR Sect 3.3.1 p. II-78
Cryomodule Length	m	16.54	15.94
Filling Factor (incl quads)		75%	70%
Real Estate Gradient	MeV/m	17.7	14.2
Energy/Cavity	MeV	26.0	22.7
Energy/Cryomodule	MeV	312.0	226.7
Linac Total Energy Gain	MeV	500000	6.7
Beam Current (peak)	mA	9.5	25.0
Power per Cavity & Coupler (peak)	kW	247	567
Cryomodules req'd for full energy		1602.6	29.6
Cryomodules Installed		1750	30
Cryomodules per vacuum Break		30	5
Vacuum Sector Length	m	496	80
Vacuum Break Cryo Insert Length	m	1	1
Total Length of Vacuum Breaks	m	58	6
Total Linac Length	m	29010	484

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## CRYOGENICS & CRYO PLANT

8 GeV Injector  
Linac

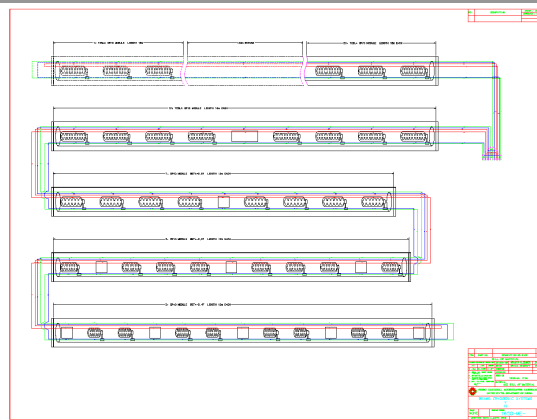
- 8 GeV Linac Cryoplant is ~ same size as SNS
  - Linac is longer: 8 GeV vs. 1 GeV
  - RF Duty Cycle is smaller 1% vs. 6%
    - *Dynamic heat load is about the same*
- 8 GeV Linac Static heat leak per meter should be similar to TESLA (TTF)
  - No bayonet or cold box heat loads per cryomodule
    - *Standby heat load should be < ~ SNS*

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## CRYOGENICS & CRYO PLANT

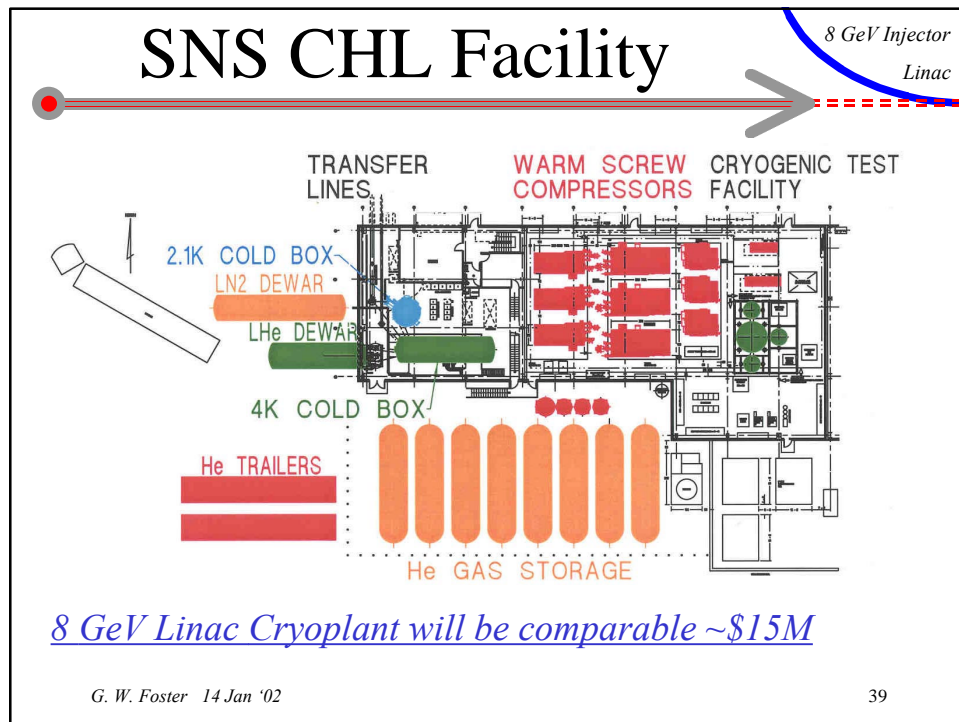
8 GeV Injector  
Linac



- Arkadiy Klebaner is doing detailed analysis of 8 GeV linac cryogenic requirements & cost

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## RF System for 1 → 8 GeV Linac

- Assume the TESLA-style RF distribution works  
*This will require development of fast phase shifters for individual cavity control*
- One TESLA multi-beam Klystron per Cryomodule
  - 24 Klystrons 10 MW each
  - Each Klystron feeds 12 Cavities in one Cryomodule
  - 288 total power couplers 600kW each
- Modulators are identical to TESLA modulators
- Rough Cost: \$1.5M / RF station ⇒ \$45M  
(TESLA costs & scaling rule\* gives ~\$31M)

\*cost proportional to (quantity)<sup>-0.074</sup>

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# Modulators for Klystrons

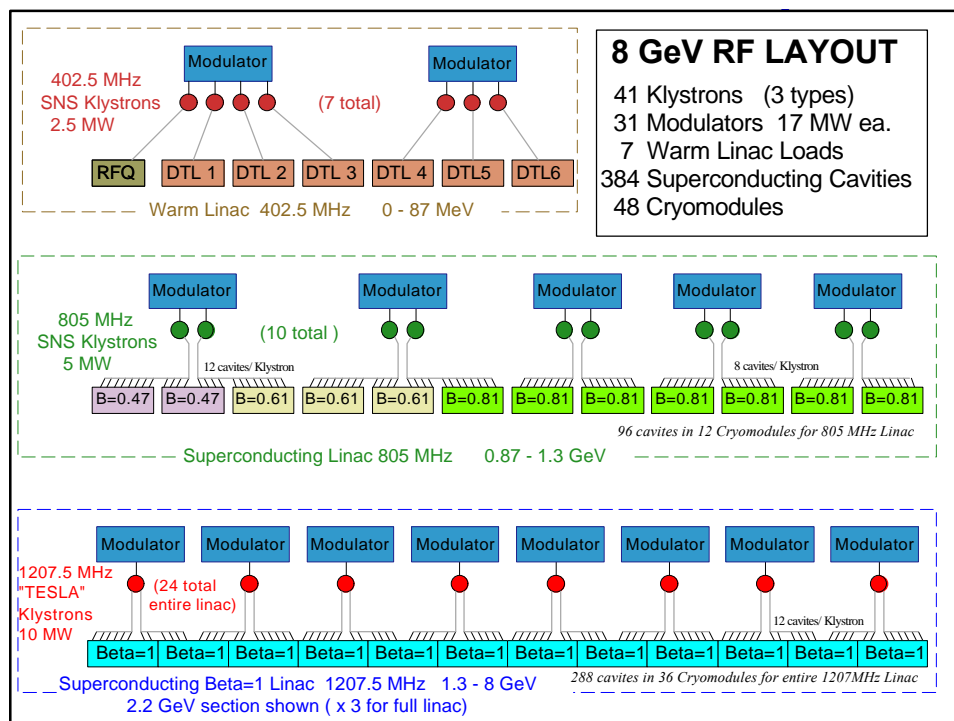
8 GeV Injector  
Linac

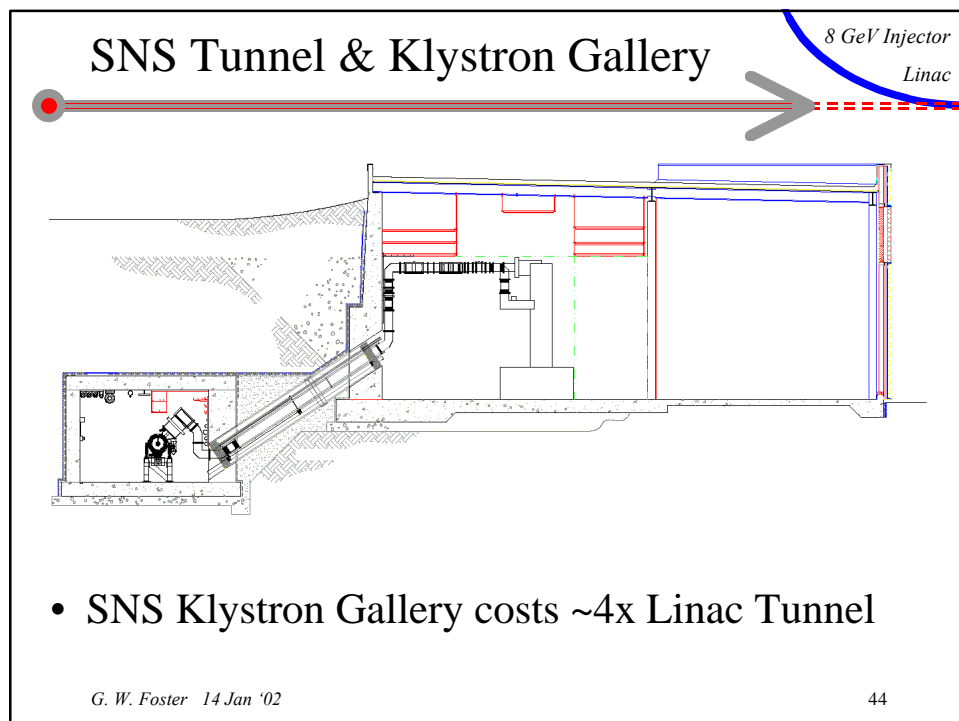
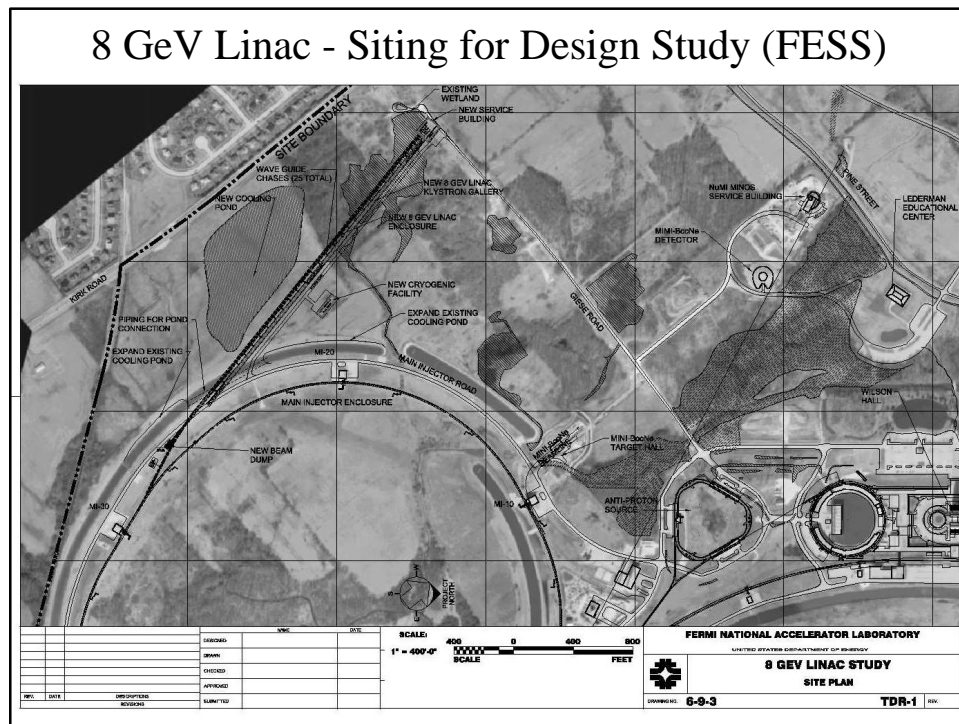


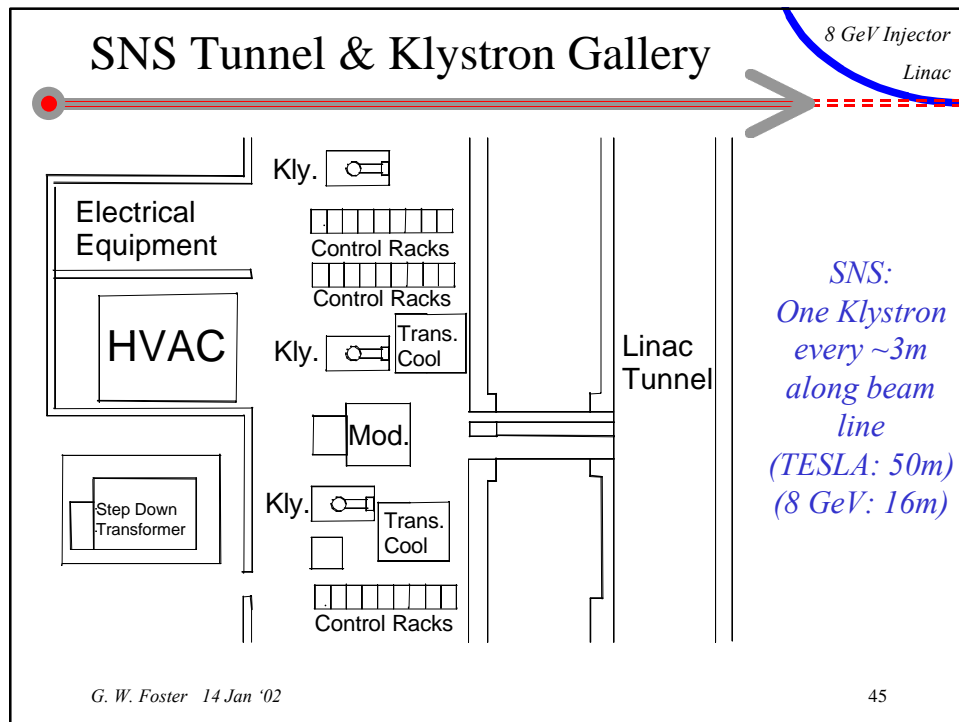
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- Biggest component in RF costs
- Pfeffer, Wolff, & Co. have been making TESLA spec modulators for years
- FNAL Bouncer design in service at TTF since 1994
- \$1M ea.

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### Note on Klystron Location

*8 GeV Injector  
Linac*

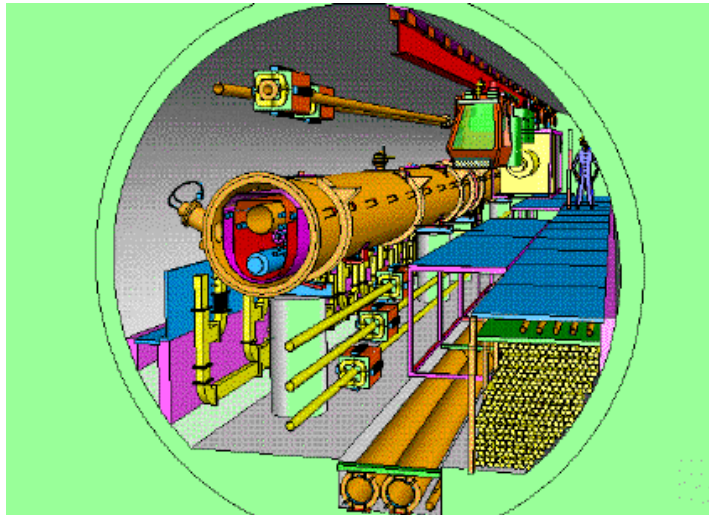
- The SNS Civil Construction (Klystron Gallery) costs could be reduced a lot if we adopt the TESLA scheme of putting the Klystron and instrumentation electronics in the tunnel, and running a fat cable to a single building with all of the modulators in it.
- This may not be an acceptable technical risk.
- In any case we save by fanning out RF drive to many cavities from small # of big Klystrons

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## TESLA Tunnel & Klystrons

8 GeV Injector  
Linac



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## SOME TECHNICAL ISSUES

8 GeV Injector  
Linac

- Main Injector Beam Current Limits
  - RF Power
  - Beam Stability
- H- Stripping & Injection at 8 GeV
  - stripping in bend magnets
  - foil issues
- RF Phasing in Linac for Protons vs. Electrons
  - transit time factors in cells and cavities
  - phase agility required of RF drive (microphonics)

OK up to  $1.5E14$  (=5x MI design)  
with RF upgrade (W. Chou PAC '97)

***P** all these must be looked at but none seem fatal*

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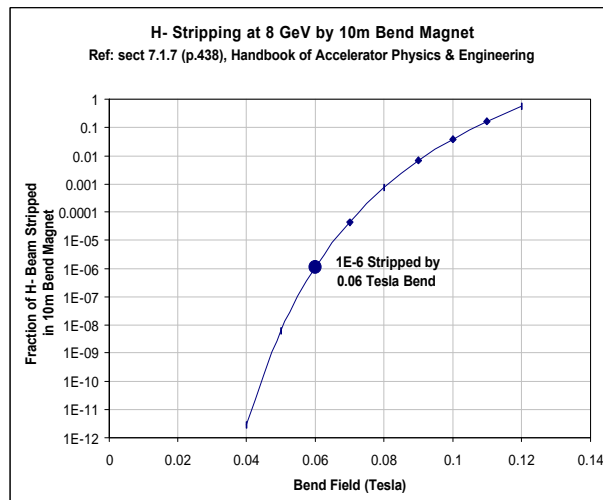
## Main Injector RF Limitations

- Existing RF System Limits (*D. Wildman*)
  - $4.5 \times 10^{13}$  ( $\sim 0.7$  A)  $\Rightarrow$  0.6 MW beam power
  - limited by beam stability given present primary amplifier tube power (installed power = 3.6 MW pk.)
  - may be increased with fast, local feedback
- Install Second Power Tube in MI RF Cavities  
(*this is provided for in the cavity design*)
  - $9 \times 10^{13}$  ( $\sim 1.4$  A)  $\Rightarrow$  1.2 MW beam power w/o feedback
  - Possible limits from cavity drift tube cooling
- Two tubes/cavity + fast feedback may reach 2MW
  - otherwise may need to build more cavities

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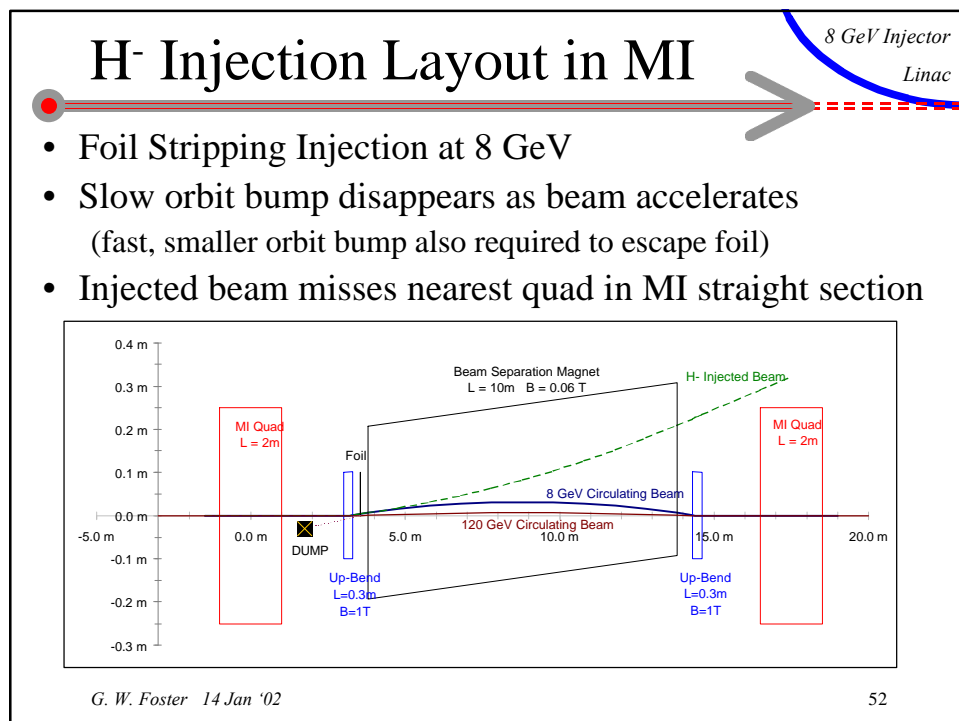
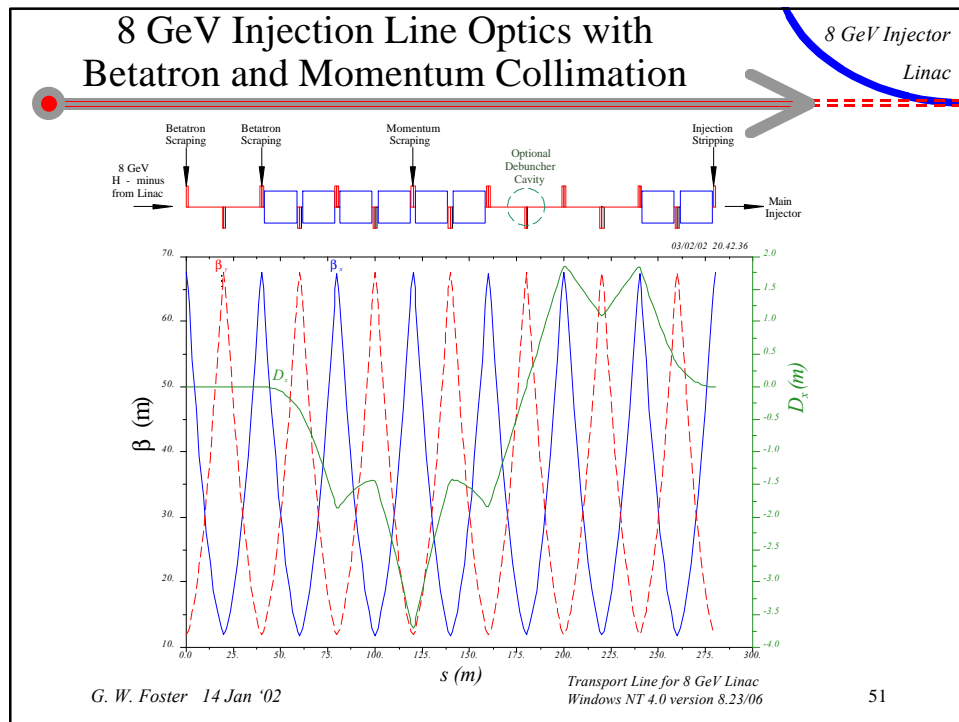
## 8 GeV H<sup>-</sup> Stripping in Magnets



- B= 0.06 Tesla strips only  $1 \times 10^{-6}$  of Beam in 10m length
- 500m Bend Radius is OK
- Stripped Beam Power is <1 Watt

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## Other H<sup>-</sup> Injection Issues

- multiple scattering in the foil
- foil lifetime
- beam dump for partially-stripped beam
- irradiation of the downstream area
- space charge tune shift limit in Main Injector
- phase space painting
- fast orbit bump & painting magnets

*P does not look like any of these are problems*

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## H<sup>-</sup> Injection Painting

(A. Drozhdin)

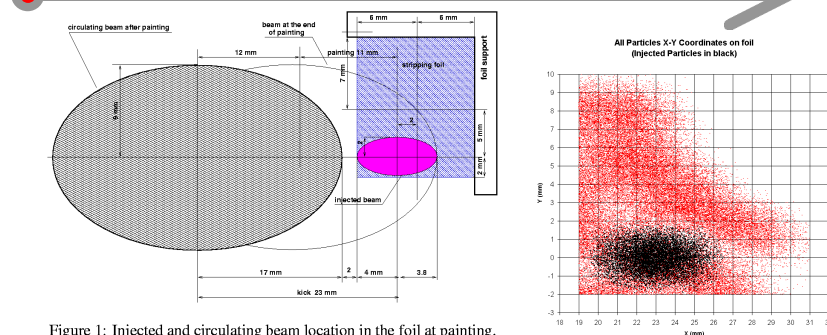


Figure 1: Injected and circulating beam location in the foil at painting.

- Painting from  $2\pi$  into  $40\pi$  with 90-turn injection seems feasible
- Peak foil temperature  $\sim 2200$  degC (tolerable)

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## RF Phasing in Linac for Protons vs. Electrons

8 GeV Injector  
Linac

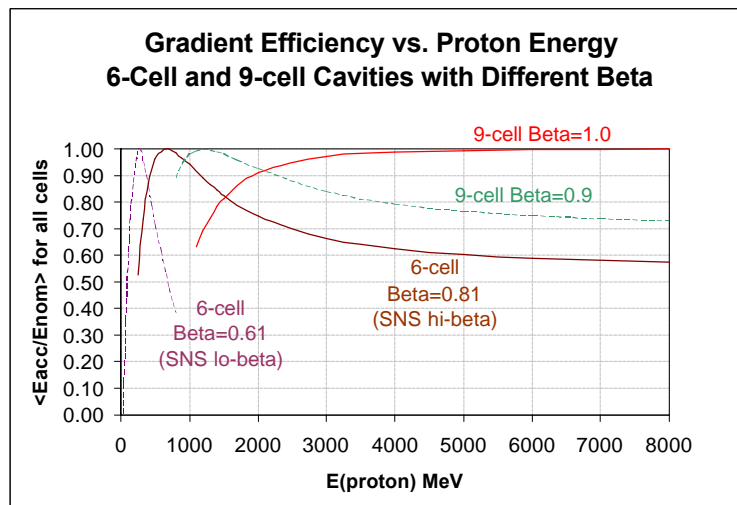
- Cavity cell length changes as proton accelerates
  - not all cavities can be same design
  - lose some gradient by running off design  $\beta$
- Protons are non-relativistic
  - energy error  $\Rightarrow$  downstream phase error
- Protons run off-crest
  - only get  $\sim 85\%$  of accelerating gradient at crest
  - more sensitive to phase errors
- Must change cavity phases to accelerate electrons and protons on alternate cycles

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## How much gradient do you lose by running cavities at the wrong $\beta$ ?

8 GeV Injector  
Linac

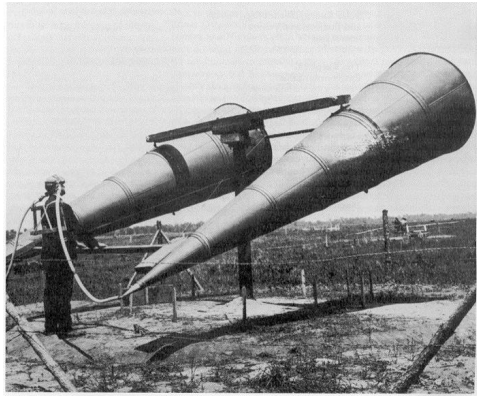


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## CAVITY MICROPHONICS

8 GeV Injector  
Linac



World War I Aircraft Detection

Within days of U.S. entry into World War I in April 1917, the Navy requested the National Research Council's help in developing a method for detecting and locating aircraft. The Research Council passed the problem along to George W. Stewart, head of the

physics department at the State University of Iowa. After some experimentation, Stewart designed a set of 18-foot-long listening horns, which were supposed to provide anti-aircraft and searchlight batteries with early warning of distant enemy aircraft. Stewart's device

never made it past the experimental stage; for field use, the American Expeditionary Forces adapted an aircraft sound locator purchased from the French. This photo shows a set of these horns undergoing trials at Ellington Field, outside of Houston, Texas, in Spring 1918.

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ISSUES IN SCIENCE AND TECHNOLOGY

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- Cavity Bandwidths are  $\sim 1 \text{ kHz}$  ( $Q \sim 10^6$ )
- Mechanical vibrations can shift resonant freq. by comparable amount.
- Produces large shift in required *phase* and *amplitude* of RF drive
- Codes exist to simulate impact on proton beams from measured (SNS/TESLA) microphonics.

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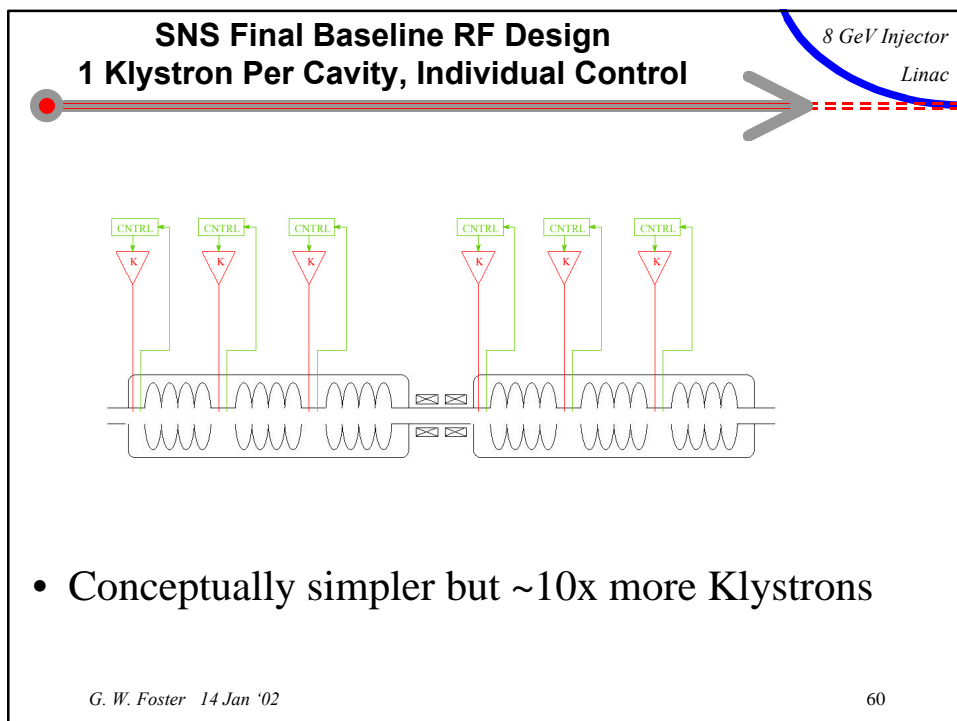
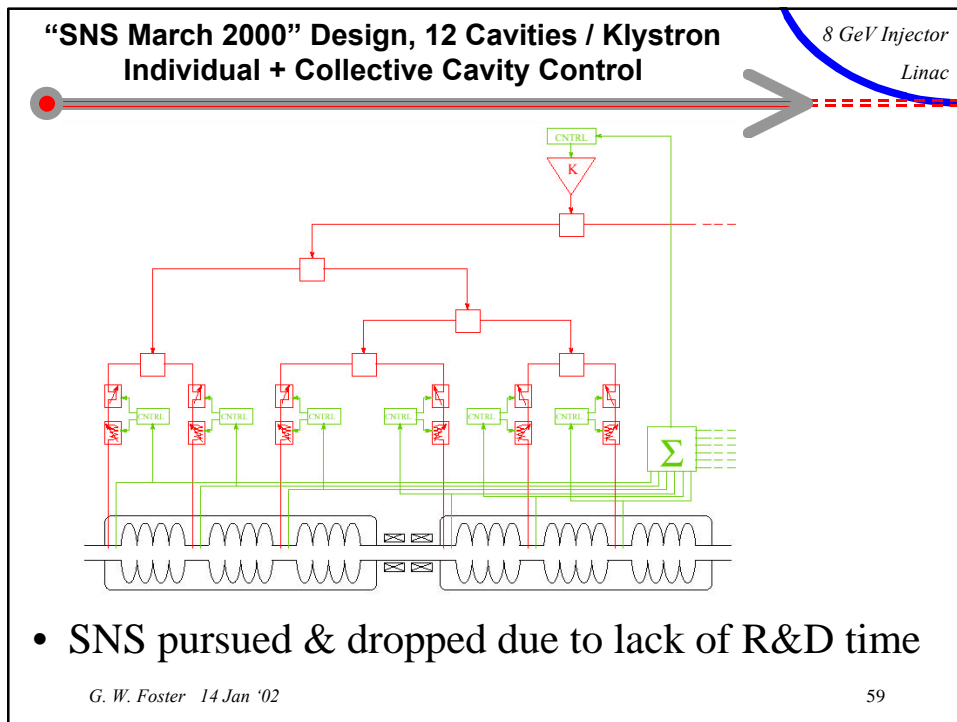
## Fast Ferrite Phase Shifter R&D

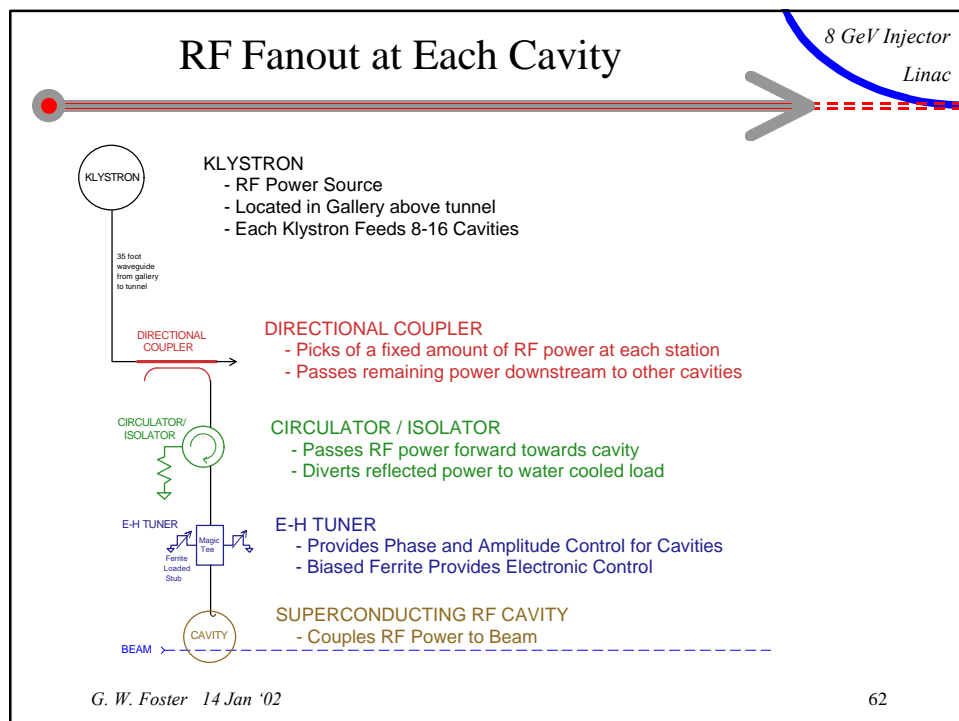
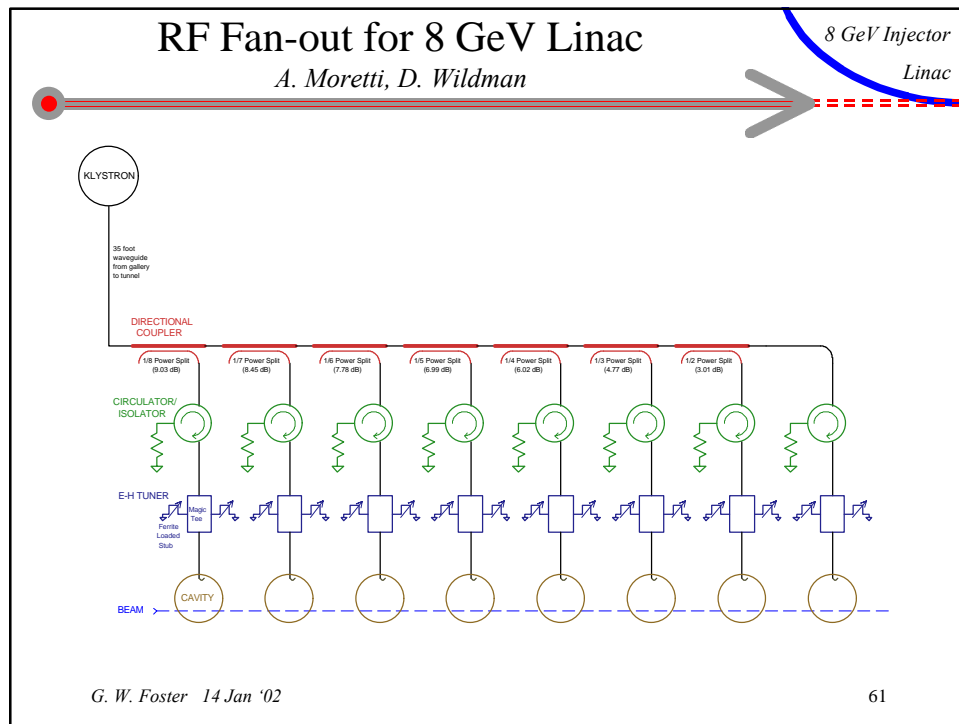
8 GeV Injector  
Linac

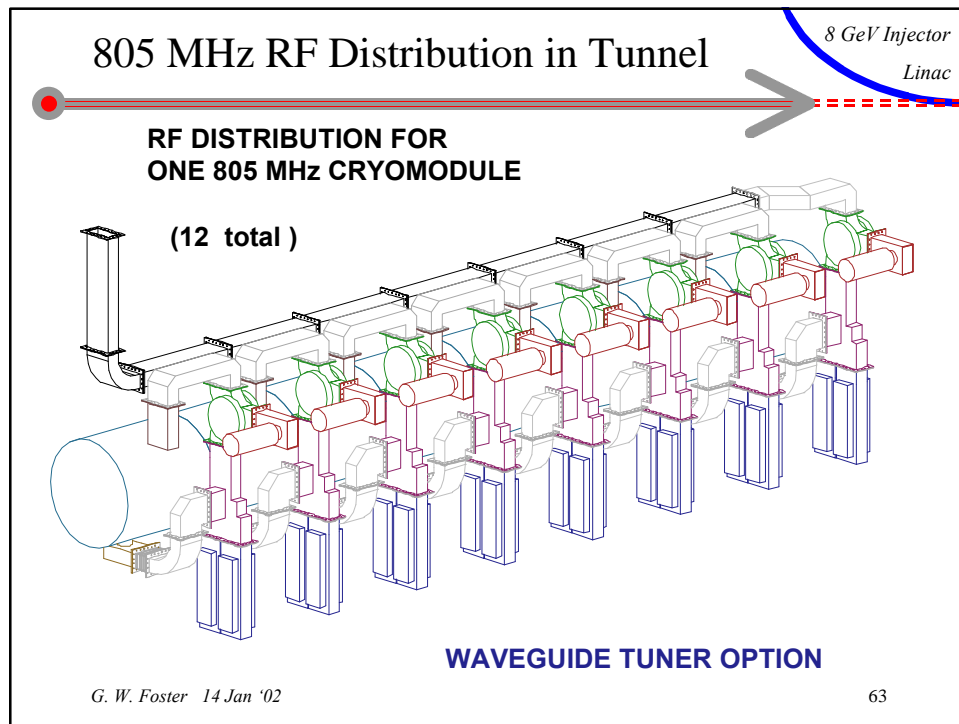
- Provide fast, flexible drive to individual cavities of a proton linac, when one is using TESLA-style RF fanout.
- Also needed if Linac alternates between e and p.
- The fundamental technology is proven in phased-array radar transmitters.
- This R&D was started by SNS but dropped due to lack of time. They went to one-klystron-per-cavity which cost them a lot of money ( $\sim \$20\text{M}$ ).

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## SECONDARY MISSIONS

8 GeV Injector  
Linac

- Main Mission: “Super-Beams” in Main Injector
- Possible Secondary Missions:
  - 1) 8 GeV Neutrino Program
  - 2) 8 GeV Spallation Neutron Source
  - 3) 8 GeV Fixed-target Program
  - 4) v-factory front end
  - 5) Electron Linac
  - 6) XFEL
  - 7) Recirculating microtron (pseudo-CEBAF)
  - 8) Pbar Deceleration
  - 9) TESLA damping ring preaccelerator linac .....

...etc... etc... etc...

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## Possible Secondary Mission #1:

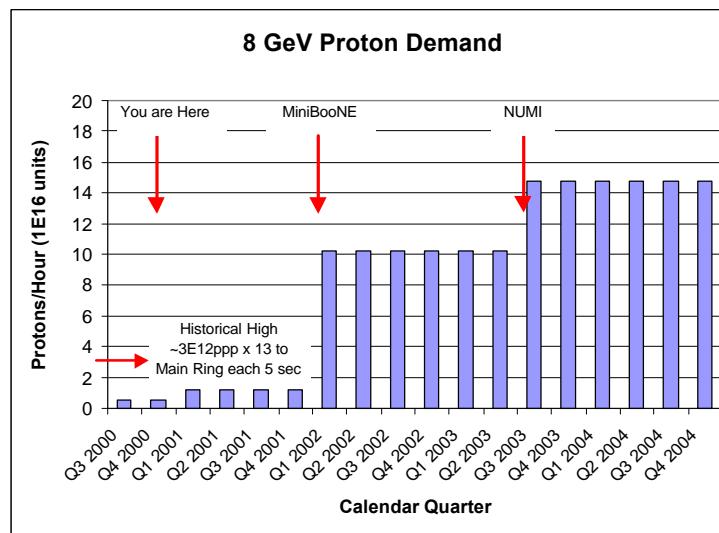
## 8 GeV Neutrino Experiments

- 8 GeV beam for Mini-BooNE follow-on
- Interleave one 8 GeV cycle(s) with MI filling  
 $> 3.6\text{E}17$  Protons/hr to *both* MI and BooNE
- Upgrade potential for  $>10$  MW of 8 GeV beam
- $\sim 20\%$  efficiency wall power  $\rightarrow$  beam
  - *Mini-BooNE confirms the LSND result, the 8 GeV linac could help increase statistics  $>20\times$ .*

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## Demand Schedule for 8 GeV Protons

8 GeV Injector  
Linac

8 GeV  
 Linac  
 $>1\text{E}18/\text{hr}$

R. Webber

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Possible Secondary Mission #2:**8 GeV Spallation Neutron Source**8 GeV Injector  
Linac

- Upgrade RF Duty cycle from 1% to ~5%
  - RF, couplers, and cryo pipe sizes must anticipate this
- Add SNS-Style Accumulator Ring (R ~ 50m)
- Biggest incremental cost will be Target facility

***8 GeV Linac has the potential be competitive as a pulsed neutron source, if FNAL is interested...***

(Installed Klystron peak power ~300MW vs. ~50 MW in SNS)

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Possible Secondary Mission #3:**8 GeV Fixed-Target Program**8 GeV Injector  
Linac

- Pion production per incident beam energy is maximized at ~6 GeV (N. Mokhov)
- ⇒ Best source for precision  $\mu$ , K experiments.
- The RF time structure (~50 psec bunches) would allow high-quality TOF separation of neutral K's
  - The Recycler might be used as 8 GeV stretcher ring to provide ~ continuous beams of protons.

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Possible Secondary Mission #4:

## Neutrino Factory

- Very Similar to 8 GeV Spallation Source (but shorter time spread on target)
- Possible to use *same linac* to *re-accelerate* the muons after filling the accumulator ring?
  - 1) use linac to fill the 8 GeV accumulator for  $\sim 1$  msec.
  - 2) rephase the cavities for muon acceleration ( $\sim 0.2$  ms).
  - 3) bunch the accumulator beam and extract onto target.
  - 4) debunch & cool the muons in couple  $\mu$ sec
  - 5) reaccelerate the muons in *same* linac at 8 GeV/turn.

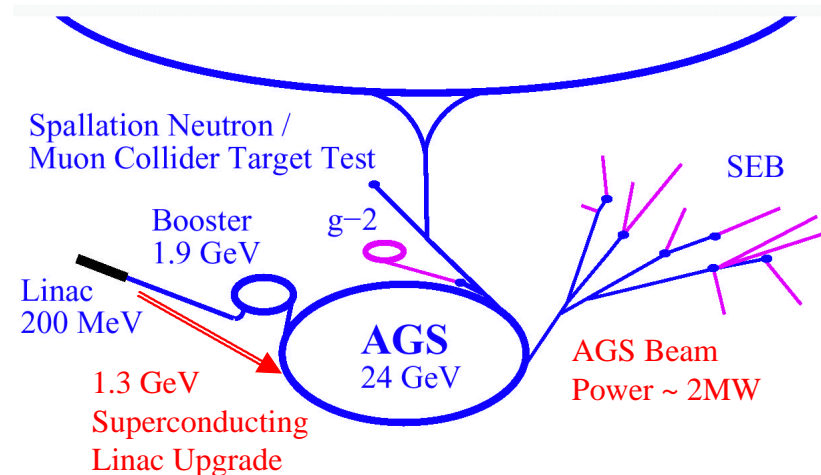
*→ everything uses DC magnets.*

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The competition:

## 1.3 GeV SC Linac for AGS Upgrade




T. Roser PAC 2001

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Possible Secondary Mission #5:**8 GeV Electron Linac**

- 
- At least 7 GeV of the linac can accelerate  $e^-$ 
    - electrons run on-crest, so the gradient will be higher  
 $\Rightarrow$  9-10 GeV e-beams
  - Re-phase the cavities for (multiple) pulses of electrons between proton injections to FMI.
    - Many possible physics missions, test beams, etc.
    - Smaller activation problems than proton beams
  - An 8-GeV Linac and SCRF infrastructure makes FNAL a good site for a super-B-factory...

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Possible Secondary Mission #6:**X-ray Free Electron Laser (XFEL)**

- 
- There may be competition for XFEL's in the U.S.
  - FNAL may want to stay out (or collaborate).
    - Concept of joint ANL-FNAL-DESY project, (sister XFEL's at DESY and FNAL), with ANL taking the lead on US XFEL user facility...?

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Possible Secondary Mission #7:

## Recirculating Electron Linac

8 GeV Injector  
Linac

- A CEBAF-Style Recirculating Linac could be made with  $\sim 8$  GeV per pass
- Smaller Duty Cycle than CEBAF, but higher energy per pass.
- Either MI or MR tunnels could hold stretcher ring to provide  $\sim$  continuous beams of *electrons*.

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Possible Secondary Mission #8:

## Antiproton Deceleration

8 GeV Injector  
Linac

Scenario:

- 1) Electron-cool Antiproton Beams in Recycler
  - 2) Ultra-cool core can be frictionally dragged away and separately extracted
  - 3) Small emittances will decelerate efficiently in large-aperture SC Linac
- $\Rightarrow$  World's best source of "stopped" antiprotons

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## VLHC and the 8 GeV Injector

- The small beam emittances obtainable with the 8 GeV Injector will make FNAL *by far* the best VLHC injector.
- Small Emittances  $\Rightarrow$  Small Beam Currents at fixed Luminosity
  - $\Rightarrow$  Small Stored Energy in Beams
  - $\Rightarrow$  Small instability problems in small beam pipes ( $\Rightarrow$  Small magnets)

	Emittance	Luminosity	Beam Current	Stored Energy
VLHC Design Study	10 pi	1.00E+34	180 mA	2.8 GJ (8x LHC)
w/ 8 GeV Injector	0.5 pi	1.00E+34	40 mA	0.6 GJ (2x LHC)

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## Proton Driver vs. 8 GeV Injector

- There is little doubt that, in principle, a synchrotron is cheaper.
- If we are manpower limited: an 8 GeV Linac has many fewer parts to design than a new Booster Synchrotron.
- The 8 GeV linac will probably be simpler to operate.
- The 8 GeV linac is more likely to produce smaller emittances, if that is the primary goal.
- It can accelerate electrons, and so has a broader range of uses.

*Difficulty with reconciling Proton Driver with B&B subpanel recommendations can be finessed by 8 GeV Linac.*

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## The Linear Collider & 8 GeV Injector

8 GeV Injector  
Linac

- If the plan is the LC, will be an advantage in asking for this \$7B project to have already completed a ~1% proof-of-principle facility showing that we understand the performance and costs.
- However in the current political climate, it may be difficult to ask for a \$100M+ proof-of-principle facility as the leading edge of a \$7B project (GWF opinion).
- FNAL needs a construction project ~ 2004 when NUMI & LHC money starts vanishing. Need to get a project into the pipeline NOW.
- The 8 GeV linac has good, stand-alone physics missions and will simultaneously provide \$200M+ "LC R&D" funds to demonstrate that we understand the performance and economics of big linacs.
- Since only the TESLA design can accelerate protons, it simplifies the LC technology choice, which can be made promptly and without contentious technology and cost comparisons.

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## Many Other Users of SCRF Linacs

8 GeV Injector  
Linac

SCRF MACHINE PARAMETERS (from JLab LLRF Conference\*)

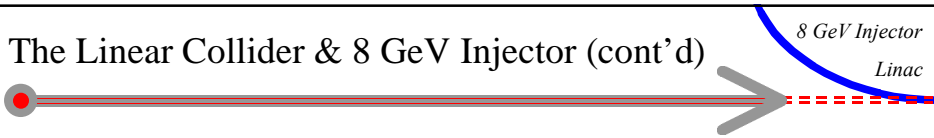
RF Parameters	Units	SNS	RIA	TESLA	12GeV CEBAF	ERLs	FEL	SPL	ELBE	
RF	MHz	805	57.5-805	1300	1500	1300 / 1500	740	352	1300	
Field	MV/m	10, 16	3 - 10	25-25	18 to 21	20	7.5	3 - 9	1 - 10	
Q <sub>loaded</sub>		7.E+05	>2E7	2.E+06	3.E+07	2.E+07	1.E+07	2.E+06	2.E+07	microphonics minimization is critical to pushing up Q in lightly beamloaded machines
beta		.61/.81	0.49/.61/.81	1	1	1	1	0.5 - 7	1	
Macro-pulse rf	msec	1.3		1.4				4		
Macro-pulse beam	msec	1		0.94				2.3		
Repetition Rate	Hz	60		5 - 10				50		
Duty Cycle		0.08		0.007	cw	cw	cw		cw	
Lorentz force coef.	Hz/(MV/m)*2	spec 2, <4 now	spec 2, <4 now	1	1 to 3	1 to 3	1 to 3	2 (LEP)	1	open issue with SNS
Beam Current, ave Macro	mA	26	0.3	9.3	0.4	-0 (<0.2)	5 to 10	13	1	FEL current is understood as unmatched beam current
Beam Phase	Degrees	-20	-30	-3	0	360	-20	-20		unclear where 1:1 tradeoff lies if performance spread of cavities is small or not in question
Number of cavity/kystrons		1	1	36	1	1?	1?	1 to 4	1	
Number of cells/cavity		6	6	9 to 18	7	9 or 7	3		9	
Microphonics(meas.)	rms Hz	10		3 to 7	3.5			?	?	clarity low end of frequency spectrum to discount easily tracked slow drifts
Pressure sensitivity				+ 10 Hz/mb				-10		near klystron saturation, slow drift effects influence tuner operation need good control headroom
Nearest mode	MHz delta	0.8	0.8	0.5, 0.3 superstructure	1?	0.8	0.8	0.7		
<b>System Requirements</b>										
Microphonics	rms Hz	15	<5	10	3.5	<11	2	10		
Amplitude stability (corr)		0.005	0.01	2.00E-04	1.10E-05	1.00E-04	1.00E-05			
Amplitude stability (uncorr)				0.001	2.00E-04	2.00E-03	6.00E-05	0.005	0.06	
Phase stability	degrees	0.5	1	0.5	0.1	0.577	??	0.5	1	
Klystron saturation	%	obscure accounting	??	3	10, under most extreme conditions	20	0		20	do SELs have a gainhoise advantage when operating near saturation? How do different machines deal with this?
Vector sum calibration	Degree / %			1 and 10						
Resonance Control - Slow	Hz	?		pm 50	-2					deadband
Resonance Control - Fast	Hz	100		pm 200	25					6 microphonics + 2" deadband
Beamloading fluctuations	%	1.2 @ 30 kHz		1	NA	2 (in most critical)	2			Low frequ

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<http://www.jlab.org/LLRF/Finalagenda.html>

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## The Linear Collider & 8 GeV Injector (cont'd)

- 
- A diagram showing a horizontal red line representing the linac, starting from a red dot on the left and ending with a large grey arrow pointing right. A dashed red line branches off to the right from the main line. A blue arc labeled "8 GeV Injector Linac" is positioned above the dashed line.
- **If TESLA is approved in the next couple of years,** then the 8 GeV Injector gives the US the opportunity to extract some benefit from our contribution to SCRF Linac technology.  
*(makes it easier to argue for a US contribution to TESLA if there is a simultaneous construction project with related technology in US)*
  - **If TESLA is NOT immediately approved,** and only TTF-2 and the 8 GeV Injector are completed, then by ~2009 this will leave the US holding the *strongest technological position to bid for the LC.*  
*(and 8 GeV linac can be used for TESLA Damping ring pre-acc.)*
  - The 8 GeV Linac holds the best promise of retaining the current construction slots in HEP (namely NUMI and the LHC), while remaining true to the strategic vision of the B&B subpanel.

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## CONCLUSIONS

- 
- A diagram showing a horizontal red line representing the linac, starting from a red dot on the left and ending with a large grey arrow pointing right. A dashed red line branches off to the right from the main line. A blue arc labeled "8 GeV Injector Linac" is positioned above the dashed line.
- An 8 GeV Injector Linac will be a useful component at FNAL no matter what future machine is built.
  - There are no technical difficulties, just further optimizations. Can copy existing designs.
  - It should make FNAL complex simpler to run.
  - The cost could be similar to the Main Injector and Proton Driver.

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